ADVANCEMENT OF A MODULAR ROTOR PERMANENT MAGNET FLUX SWITCHING MACHINE FOR HIGH TORQUE PERFORMANCE

IRFAN ALI SOOMRO

A thesis submitted in
fulfilment of the requirement for the award of the
Degree of Master of Electrical Engineering

Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

JANUARY 2021

I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged

Student: ……………………………………….

IRFAN ALI SOOMRO

Date: 13-01-2021

Supervisor: ……………………………………….

ASSOCIATE PROF. IR. DR ERWAN BIN SULAIMAN

To my beloved mother and father...

ACKNOWLEDGEMENT

First of all, I am thankful and grateful to Almighty ALLAH for giving me courage and helping me to finish my master's studies successfully.

I count myself very fortunate to work under the supervision of Associate Prof. Ir. Dr. Erwan Bin Sulaiman, who is so generous with his time and efforts guiding me effectively throughout the entire research process. Without his constructive and critical comments, continues encouragement and good humor while facing difficulties, I could have not completed this research. I am also very grateful to him for guiding me to think critically and independently.

I would also like to acknowledge with thanks, to my parents and family members for their moral and financial support towards the completion of my study. Specially, my older and younger brother Associate Prof. Dr. Mukhtiar Ali Soomro and Imran Ali Soomro. Moreover, A sincere thanks to my beloved sister Nguyen Thi Dep, who always encourage and motivated me during my research.

I acknowledge, with many thanks, to UTHM technical staff and my lab members specially, Dr. Enwelum Mbadiwe Ignatius, Hassan Ali Soomro, Faisal Amin, Syed Naufal, Mohd Fairoz, Mohd Firdous and Miss Laili, who never turned me down whenever I went to them with questions. Furthermore, I would like to acknowledge, with many thanks, to my friends specially Amir Ali Detho, Dr. Shalini Sanmargaraja and Dr. Abdul Rashid Omar Mumin. They encouraged and motivated me during my research.

Moreover, it has been a very pleasant and enjoyable experience to work in UTHM with a group of highly dedicated people, who have always been willing to provide help, support and encouragement whenever needed. I would like to thank all my fellow friends during my study in UTHM. Life would never have been that existing and joyful without you all. Finally, I would like to thank everybody who was important to the successful realization of this thesis, as well as expressing my apology that I could not mention personally one by one.

ABSTRACT

Usage of electric motors in electric vehicle applications have gained a lot of attention since the motor must possessed high torque density and power. Permanent magnet flux switching machines have attracted considerable interests in recent years since the flux focusing is utilizable, both armature windings and PM excitation sources are on the stator, and the salient pole rotor is simple yet robust. Regrettably, salient rotor and stator of PMFSM with single tooth winding have inherited flux cancellation, flux leakage, high iron losses, high winding losses, and longer flux paths which reduced the torque and efficiency of the motor. In this thesis, a flux switching motor using permanent magnet employing modular rotor is designed and investigated for high torque making it suitable for high torque performances applications. The design engaged a three-phase 12 stator tooth taking up four sets of windings per phase with 10 pole feasible modular rotor. The characteristics performance of modular rotor PMFSM were designed and analysed using JMAG designer 14.1 utilizing 2D finite element analysis (2D-FEA). The initial 12S/10P modular rotor PMFSM topology achieved an average torque of 34.44 Nm with an output power of 5.67 kW. To further improve the performance of modular rotor PMFSM, local optimization approach was conducted which achieved an average torque of 60.49Nm and an output power of 23.34 kW while maintaining the same motor's outer diameter. Furthermore, to compare modular rotor PMFSM with salient rotor PMFSM, FEFSM and HEFSM were utilized to choose best candidate for high torque performance. In comparison, optimized modular rotor PMFSM generated the highest output torque followed by optimized salient rotor HEFSM which generated the second highest torque. Consequently, the modular rotor PMFSM produced higher average torque, less iron losses, less weight and shorten flux path than using salient rotor pole PMFSM, FEFSM or HEFSM. In conclusion, modular rotor PMFSM confirms good agreement with high torque applications.

ABSTRAK

Penggunaan motor elektrik dalam aplikasi kenderaan elektrik telah mendapat banyak perhatian kerana motor tersebut mestilah mempunyai ketumpatan daya tork dan kuasa yang tinggi. Mesin penukar fluks magnet kekal telah menarik minat yang besar dalam beberapa tahun kebelakangan ini kerana pemfokusan fluks yang dapat digunakan, kedua-dua belitan angker dan sumber pengujaan PM berada di stator, serta rotor kutub menonjol yang ringkas namun kuat. Malangnya, rotor menonjol dan stator PMFSM dengan belitan gigi tunggal telah mewarisi pembatalan fluks, kebocoran fluks, kehilangan besi serta belitan yang tinggi, dan mempunyai jalur fluks yang lebih panjang menyebabkan pengurangan tork dan kecekapan motor. Dalam tesis ini, sebuah motor penukar fluks menggunakan magnet kekal menggunakan rotor modular telah direka dan dikaji untuk menghasilkan tork yang lebih tinggi agar sesuai diaplikasikan pada kenderaan elektrik. Reka bentuknya menggunakan tiga fasa 12 gigi stator yang mengambil empat set belitan bagi setiap fasa dengan 10 kutub rotor modular. Prestasi ciri PMFSM rotor modular direka dan dianalisis menggunakan pereka JMAG 14.1 yang mempunyai analisis unsur terhingga 2D (2D-FEA). Topologi rotor modular PMFSM 12S/10P pada awalnya mencapai tork purata 34.44 Nm dan kuasa keluaran 5.67 kW. Untuk meningkatkan lagi prestasi rotor modular PMFSM, pendekatan pengoptimuman tempatan dilakukan dan mencapai purata tork 60.49 Nm dan kuasa keluaran sebanyak 23.34 kW disamping mengekalkan diameter luar motor yang sama. Selain itu, perbandingan antara rotor modular PMFSM dengan rotor menonjol PMFSM, FEFSM dan HEFSM telah dilakukan untuk mengenalpasti tork yang tertinggi. Sebagai perbandingan, rotor modular PMFSM yang dioptimumkan menghasilkan tork keluaran tertinggi diikuti dengan rotor menonjol HEFSM dioptimumkan yang menghasilkan tork output kedua tertinggi. Oleh yang demikian, rotor modular PMFSM menghasilkan tork purata yang lebih tinggi, kurang kehilangan besi, lebih ringan dan memendekkan jalur fluks berbanding dengan menggunakan rotor menonjol PMFSM, FEFSM atau HEFSM. Kesimpulannya, rotor modular PMFSM merupakan persetujuan yang baik dengan aplikasi-aplikasi tork yang tinggi.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

ψ	-	Flux linkage due to excitation components
ϕ_m	-	PM flux linkage
α_a	-	Filling factor of armature coil
α_{cog}	-	Electrical angle of rotation
α_f	-	Filling factor
η	-	Efficiency
θ	-	Electrical angular position of rotor
ω_r	-	Rotational speed
ρ	-	Copper resistivity
B_n	-	Magnetic flux density
f_e	-	Electrical frequency
f_m	-	Mechanical rotation frequency
H	-	Height of coil slot
I_a	-	Armature coil current
i_d	-	d-axis current
i_q	-	q-axis current
J_a	-	Armature current density
kW	-	Kilowatt
ℓ	-	Stack length
L	-	Coil length
$L_{a,e}$	-	Stack length of machine
$L_{a\text{-}end}$	-	Estimated average length of armature end coil
L_d	-	d-axis inductance
$L_{a\text{-}end}$	-	Estimated average length of field excitation end coil

L_f	-	Total series inductance of field coil
L_q	-	q-axis inductance
N	-	Number of turns
n	-	Number of elements
N_a	-	Number of turns of armature coil
$N_{a\text{-}slot}$	-	Number of slots of armature coil
$N_{a\text{-}slot}$	-	Number of slots of armature conductor
N_p	-	Number of periods of cogging torque
N_r	-	Number of rotor pole
N_s	-	Number of stator slot
p	-	Pole pairs number
P_a	-	Armature coil loss
P_c	-	Copper loss
P_i	-	Iron loss
P_{max}	-	Maximum power
P_o	-	Output power
q	-	Number of phases
R_a	-	per-phase armature coil resistance
R_c	-	iron core resistance
R_f	-	Total series resistance of field coil
R_{in}	-	Inner radius of coil end
R_{out}	-	Outer radius of coil end
S_a	-	Armature coil slot area
T_e	-	Electromagnetic torque
T_L	-	Load torque
T_{max}	-	Maximum torque
V_1	-	Volume of coil slot
V_2	-	Volume of coil end
V_{total}	-	Total volume of coil
W	-	Width of coil slot
$x_{d,q}$	-	Components in d-q axis

$x_{u,v,w}$	-	Components of U, V, and W phase
AC	-	Alternating current
AlCiRaF		Alternate Circumferential Radial Flux
DC	-	Direct current
EM	-	Electric motors
EV	-	Electric vehicle
FE	-	Field excitation
FEA	-	Finite Element Analysis
FEC	-	Field Excitation Coil
FEFSM	-	Field excitation flux switching motor
FSM	-	Flux switching motor
HE	-	Hybrid Excitation
HEFSM-		Hybrid excitation flux switching motor
HEV	-	Hybrid Electric Vehicle
IPMSM	-	Interior permanent magnet synchronous motor
LOA	-	Local optimisation approach
ModR		Modular rotor
PM	-	Permanent magnet
PMDC		Permanent magnet direct current motor
PMFSM	-	Permanent magnet flux switching motor
PMSM	-	Permanent magnet synchronous motor
SPMSM	-	Surface mounted permanent magnet synchronous motor
SRM	-	Switched reluctance motor

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of study

The problem of global warming in the 21st century is a major public concern today. A variety of detailed experiments have also been carried out by certain parties to show that this is not an unusual issue that needs to be overlooked, but instead, to come out with collection of studies, promising proposals and viable solutions[1]-[5]. As stated in [1]-[2], the release of man-made greenhouse gasses [GHGs] is one of the key factors leading to the escalation of global warming. Carbon dioxide (CO_2) is identified as one of the major greenhouse gasses released into the atmosphere by the combustion of fossil fuels[3].

The conventional internal combustion engine (ICE) has been used in vehicles for personal travel for more than 100 years. At present, the market for private vehicles is growing as the world's population is growing rapidly. Emission is the critical problem associated with usage of private vehicles. This has become a significant factor to global warming, which has been an acute issue that must be faced by everyone. As a result, the government and related agencies have come up with better regulations to address the issue of emissions and fuel efficiency. In order to achieve a full-range, high-efficiency vehicle while reducing pollution of emissions, the most feasible solution at present is an electric vehicle (EV) powered by a battery-charged electric motor[6-10]. Generally, there are several important steps and attention needs to be taken to select an electric motor for EV propulsion systems. In fact, the automotive industry is still hunting for the most appropriate electrical propulsion system for EVs.

The main features of this case are performance, reliability, and cost. The selection process for the suitable electrical propulsion systems will be carried out at the system level. The option of electrical propulsion systems for EV depends primarily on three factors: driver preferences, vehicle size constraints and energy source. For these criteria, it is known that it is difficult to identify different motor operating points[11]. Choosing the most suitable electrical propulsion device for the EV is thus always a challenging job. At present, the major type of electric motors under serious consideration for EVs is the Flux Switching Machine (FSM), which has recently become a well-known and appealing machine type due to its various advantages such as high torque density and efficiency[12-16].

Flux switching Machine (FSM) was introduced in 1955 as a single-phase alternator by Rauch and Johnson [17], which consists permanent magnet as the single magnetic flux source and has been receiving significant attention afterwards especially in electric propulsion system application and meanwhile, the first three-phase system was later developed in 1997 by E. Hoang *et al* [18]. Firstly, the invented permanent magnet flux switching machine (PMFSM), which is a permanent magnet (PM) single-phase limited angle actuator, or more well known as Laws relay [110,111], with four stator slots and four rotor poles was developed. It is then extended into a single-phase generator with four stator slots and four or six rotor poles. FSM comprises all flux sources in the stator and besides the advantage of brushless machines type, FSM also has a single piece of iron rotor structure that is robust and applicable for high-speed applications [19]. Over the past ten years, many new FSM topologies have been developed for various applications, ranging from low-cost domestic appliances, automotive, wind power, aerospace, and others [20].

In general, FSM can be broken down into three major clusters namely permanent magnet flux switching motor (PMFSM), field excitation flux switching motor (FEFSM) and hybrid excitation flux switching motor (HEFSM). Both PMFSM and FEFSM have only one single main excitation flux source, respectively induced by permanent magnet and field excitation coil (FEC) whereas both PM and FECs are being used to generate flux in HEFSM. On the other hand, the armature winding and permanent magnet are both stationary in PMFSM, but magnetic flux linkage can be altered either positive or negative polarity depends on the position of the rotating part. The concept of FSM is involves changing the polarity of the flux linking the armature winding by motion of the rotor [21]. Finally, the excitation flux produced by permanent magnet flows from stator to rotor and oppositely from rotor to stator in order to accomplish one complete cycle. Similarly, this particular operation and principle take place for the rest of FEFSM and HEFSM as well.

Based on literature, first PMFSM was introduced as a single-phase alternator by Rauch and Johnson in 1955 [12] and has been getting momentous consideration subsequently especially in electric force system application. Meanwhile the first three phase permanent magnet flux switching machine was established in 1997 by E. Hoang *et al*. [18]. The conventional design is, however, receive the drawbacks of high PM volume. Hence, variety of PMSFM designs has been introduced ever since. For reducing the number of PM consumption, the stator poles are substituted alternately by a simple stator tooth and consequently the new E-core is established [13] as shown in Figure 1.1(a). The E-core configuration is validated with the mixture of radial and circumferential directions of PM as shown in Figure 1.1(b).

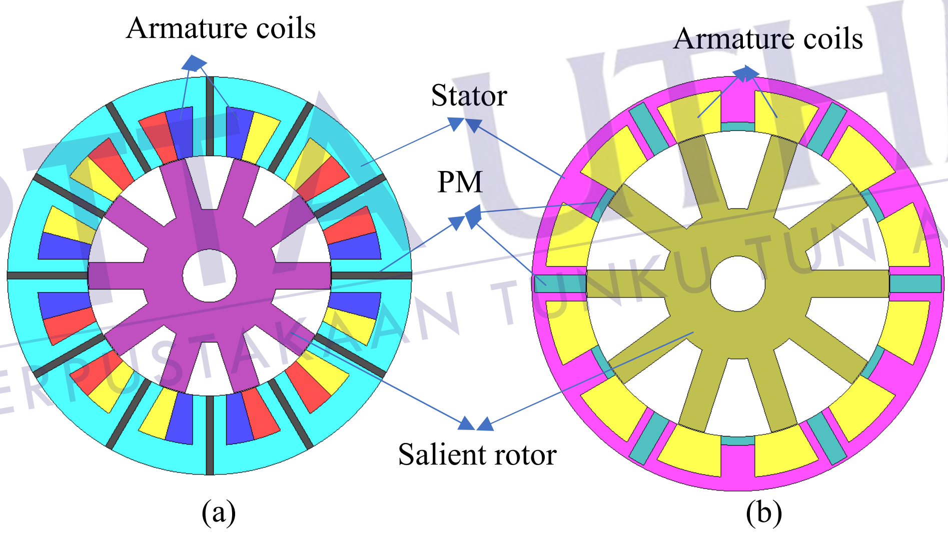
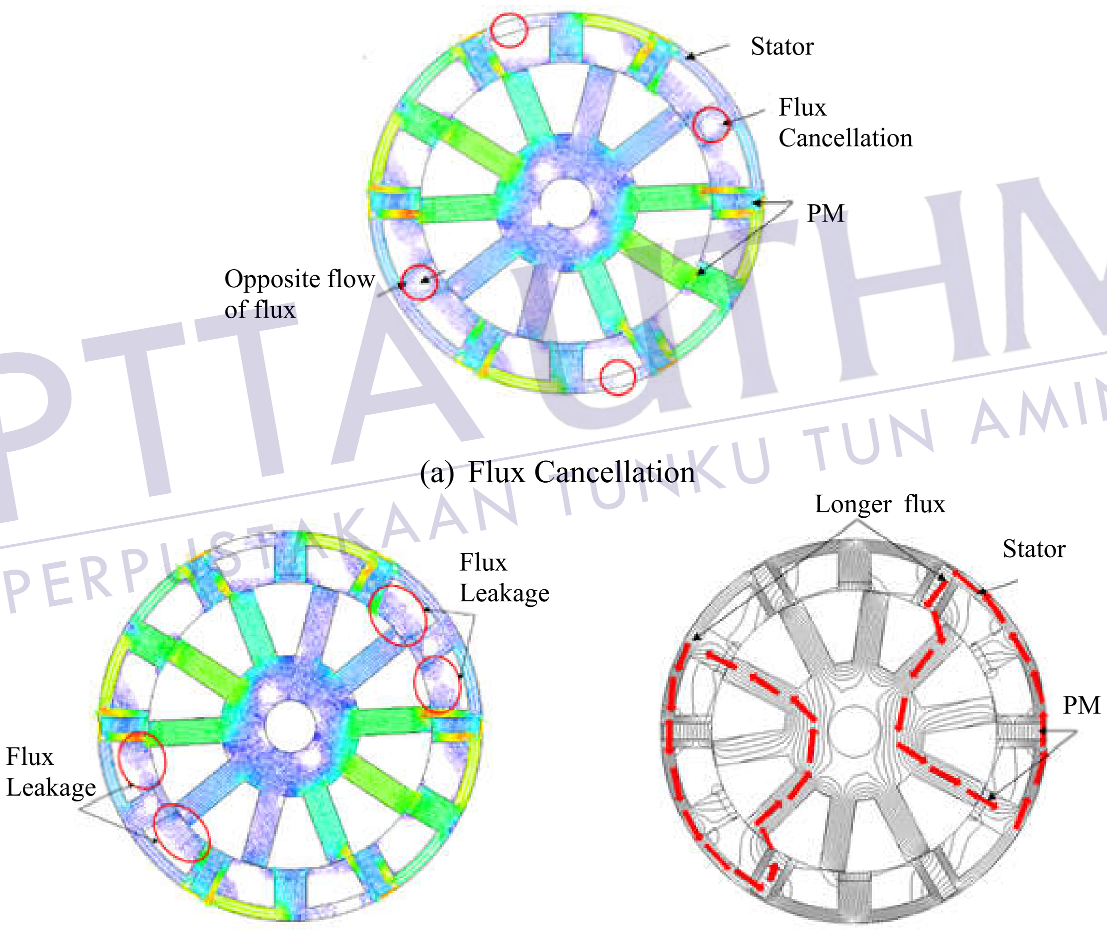


Figure 1.1: (a) Conventional PMFSM (b) 12S-10P AlCiRaF PMFSM

1.2 Problem statement

Recently another design is established in PM with alternate circumferential and radial direction [15,16] as shown in Figure 1.1 (b). But there are some drawbacks of alternate circumferential and radial (AlCiRaF) PMFSM that reduce the torque and efficiency of the motor, such as flux cancellation, longer flux paths and flux leakage. In the Figure 1.2 (a), red circles show the areas where fluxes are cancelled due to opposite fluxes produced by the radial and circumferential source pattern. For the flux leakage illustrated in Figure 1.2 (b), it is a result of geometry arising from the stator tooth width which is not large enough for the flow of flux. Furthermore, when the stator tooth housing the flux source aligns with a rotor tooth, flux flows from it into the rotor tooth and links with the adjacent stator pole and linking the adjoining rotor to complete a full cycle thus following a longer path as shown in Figure 1.2(c).

Therefore, to deal with all above mentioned limitations, novel configuration of PMFSM based on modular rotor is proposed that will ensure less use of materials is proposed for high torque performance.



(a) Flux Cancellation

(b) Flux Leakage

(c) Longer flux path

Figure 1.2: (a) Flux cancellation (b) Flux leakage (c) Longer Flux path

1.3 Aim and objectives of study

The main aim of this research is to develop a novel structure of modular rotor with permanent magnet flux switching motor (PMFSM) for electric vehicles applications. In order to achieve the main aim, there are some specific objectives that would be fulfilled, which are:

(i) To design and investigate the performance of a modular rotor based PMFSM in order to reduce the longer flux path in rotor.

(ii) To enhance the performance of modular rotor PMFSM by working on cogging torque, back emf, average torque, output power, efficiency, and torque-speed characteristics by using local optimization method based on changing all sensitive parameters.

(iii) To compare initial and optimized design of modular rotor PMFSM with the initial and optimized designs of salient rotor FEFSM, PMFSM and HEFSM, to choose a best candidate for high torque performance.

1.4 Scope of the study

This research focuses on the design of modular rotor permanent magnet flux switching motor for lightweight electric vehicle application. The scopes of the research are the following:

(i) Design the 12S/10P modular rotor PMFSM using the commercial JMAG Designer version 14.1 and analyzed by 2D-FEA.

(ii) The motor diameter is 150 mm, stack-length is 70 mm and airgap is 0.3 mm all are fixed.

(iii) The limit of the bus voltage is 415 DC V, armature current density J_a is set to a maximum of 30 A_{rms}/mm^2. Examination of coil test is conducted on the armature winding, the operating principle of the proposed motor is performed and verified. The electromagnetic performances such as peak magnetic flux linkage, cogging torque, induced back-emf will be analyzed. Furthermore, torque-speed characteristics are conducted by varying the armature phase angle from 0-80 degrees and average torque using 2D-FEA. Finally, motor losses such as iron and copper are computed based on FEA and formula.

(iv) The Local optimization approach is selected from several other methods because of its flexibility. The method is able to analyses the performance of the electric motor with each parameter freely adjusted.

(v) Comparison of FEFSM, PMFSM and HEFSM with the new modular rotor PMFSM by resizing the current design to the new 150 mm outer diameter.

1.5 Significant of study

All electric vehicle (EV) propelled by electric motor (EM) powered by stored electricity as electric vehicles are road user friendly, does not depend on fuel oil for propulsion. It is obvious that transiting to reliable EVs propelled EM will be embraced by various governments across the world as solution for the high cost and maintenance of ICE with depleting oil reserve. Furthermore, demand of EVs will be high due to durability, reliability, excellent performance, and low cost. The work in this thesis can lay claim to have provided new insights in the following aspects:

(i) Feasible configurations of three-phase flux switching motor (FSM) employing modular rotor using permanent magnet (PM) as excitation flux have been designed.

(ii) FSM employing rotor segment/modular is found to be capable of an optimal torque. The modular rotor also offers reduction in rotor mass over conventional rotor topology due to a smaller number of PMs and uses less iron material in rotor.

(iii) Local optimization approach is utilized to improve the motor performance, compared with existing FSMs using salient rotor pole.

1.6 Thesis organization

This thesis is structured into the following chapters:

Chapter 1 covers introduction, problem statement, research objectives to solve the problems, scope of work and structure of thesis.

Chapter 2 presents the overview of flux switching motors that summarizes the basic theory and classification of FSM including the examples of PMFSM, FEFSM

REFERENCES

1. Bose, B. K. Global warming: Energy, environmental pollution, and the impact of power electronics. *IEEE Industrial Electronics Magazine*. 2010. 4(1): 6 - 17.
2. Mills, W., Heidel, K., & Chung, C. F. Alternative earth-based and space-based techniques for mitigating global climate change: What can we learn by examining them? *IEEE EIC Climate Change Conference.* 10-12 May. Ottawa, ON, Canada. IEEE. 2006. pp. 1-10.
3. Kumar, H. and Ravikumar, S. An approach of CO_2 capture technology for mitigating global warming and climate change-an overview. *Recent Advances in Space Technology Services and Climate Change (RSTS & CC*). 13-15 November. Chennai, India: IEEE. 2010. pp. 364-371.
4. Pal, S. Wind energy — An innovative solution to global warming?" *1st International Conference on the Developments in Renewable Energy Technology (ICDRET)*. 17-19 Dec. Dhaka: IEEE 2009. pp. 1-3.
5. Singh, B. R., & Singh, O. 21st Century challenges of clean energy and global warming-can energy storage systems meet these issues? *3rd International Conference on Thermal Issues in Emerging Technologies Theory and Applications*. 19-22 Dec. Cairo, Egypt: IEEE. 2010. pp. 323-329.
6. Chan, C. C. The state of the art of electric, hybrid, and fuel cell vehicles. *Proceedings of the IEEE*. 2007. 95(4): 704-718.
7. Ehsani, M., Gao, Y., & Miller, J. M. Hybrid electric vehicles: Architecture and motor drives. *Proceedings of the IEEE*, 2011. 95(4): 719-728.
8. Gao, D. W., Mi, C., & Emadi, A. (2007). Modeling and simulation of electric and hybrid vehicles. *Proceedings of the IEEE*, 2009. 95(4): 729-745.
9. Sulaiman, E., Kosaka, T., & Matsui, N. Design optimization and performance of a novel 6-slot 5-pole PMFSM with hybrid excitation for hybrid electric vehicle. *IEEJ Transactions on Industry Applications*, 2012. 132(2): 211-218.
10. Rahman, Z., Ehsani, M., & Butler, K. L. (2000). An investigation of electric motor drive characteristics for EV and HEV propulsion systems. *SAE*

transactions Technical Paper, 2000. 2396-2403.

11. Eudy, L., & Zuboy, J. *Overview of advanced technology transportation*, Update (No. DOE/GO-102004-1849). 2004. National Renewable Energy Lab., Golden, CO (US).
12. Sulaiman, E. B., Kosaka, T., & Matsui, N. Design study and experimental analysis of wound field flux switching motor for HEV applications. *XXth International Conference on Electrical Machines.* 2-5 Sept. Marseille, France. IEEE: pp. 1269-1275.
13. Fei, W., Luk, P. C. K., Shen, J., & Wang, Y. A novel outer-rotor permanent-magnet flux-switching machine for urban electric vehicle propulsion. *3rd International Conference on Power Electronics Systems and Applications (PESA)* 01 September. Hong Kong, China: IEEE. 2009. pp. 1-6.
14. Hua, W., Cheng, M., Zhu, Z. Q., & Howe, D. Analysis, and optimization of back-EMF waveform of a novel flux-switching permanent magnet motor. *IEEE Transactions on Energy Conversion.* 2008. 2(3): 1025-1030.
15. Amara, Y., Barakat, G., Paulides, J. J. H., & Lomonova, E. A. Overload capability of linear flux switching permanent magnet machines. *Applied Mechanics and Materials*. 2013. 416-417: 345-352.
16. Ahmad, M. Z., Sulaiman, E., Jenal, M., Utomo, W. M., Zulkifli, S. A., & Bakar, A. A. Design investigation of three phase HEFSM with outer-rotor configuration. *IEEE Conference on Clean Energy and Technology (CEAT)*. 18-20 Nov: IEEE. 2013. pp. 220-225.
17. Rauch, S. E., & Johnson, L. J. Design principles of flux-switch alternators. *Transactions of the American Institute of Electrical Engineers. Part III: Power Apparatus and Systems*, 1955. 74(3): 1261-1268.
18. Hoang, E., Ahmed, H. B., & Lucidarme, J. Switching flux permanent magnet polyphased synchronous machines. *7th Eur. Conf. Power Electronics and Applications*, 3: 1997. pp. 903–908.
19. Mazlan, M. M. A., Sulaiman, E., & Kosaka, T. Design study of single-phase outer-rotor hybrid excitation flux switching motor for hybrid electric vehicles. *IEEE 8th International Power Engineering and Optimization Conference*. 24-25 March. Langkawi, Malaysia: IEEE. 2014. pp. 138-143.
20. Sulaiman, E. *Design Studies on Less Rare-Earth and High-Power Density Flux Switching Motors with Hybrid Excitation / Wound Field Excitation for HEV*

Drives. Ph.D. thesis. Nagoya Institute of Technology Nagoya, Japan; 2012.

21. Sulaiman, E., Kosaka, T., & Matsui, N. A novel hybrid excitation flux switching synchronous machine for a high-speed hybrid electric vehicle application. *International Conference on Electrical Machines and Systems* 20-23 Aug. Beijing, China: IEEE. 2011. pp. 1-6.
22. Sanabria-Walter, C., Polinder, H., & Ferreira, J. A. High-torque-density high-efficiency flux-switching PM machine for aerospace applications. *IEEE journal of emerging and selected topics in power electronics*, 2013. 1(4), 327-336.
23. Gaussens, B., Hoang, E., Lécrivain, M., Manfe, P., & Gabsi, M. A hybrid-excited flux-switching machine for high-speed DC-alternator applications. *IEEE Transactions on industrial electronics*, 2013 61(6), 2976-2989.
24. Pollock, C., & Brackley, M. Comparison of the acoustic noise of a flux-switching and a switched reluctance drive. *IEEE Transactions on Industry Applications*. 2003. 39(3), 826-834.
25. Jeong, G., Hwang, H., Kim, D., Kim, T., & Lee, C. (2016, November). Acoustic noise and vibration reduction of flux-switching permanent magnet machine for elevator door application. *IEEE Conference on Electromagnetic Field Computation (CEFC)*. 13-16 Nov. Miami, FL, USA: IEEE. pp. 1-1.
26. Bangura, J. F. Design of high-power density and relatively high-efficiency flux-switching motor. *IEEE Transactions on Energy Conversion*. 2006. 21(2), 416-425.
27. Fang, Z. X., Wang, Y., Shen, J. X., & Huang, Z. W. (2008, April). Design and analysis of a novel flux-switching permanent magnet integrated-starter-generator. In 2008 *4th IET Conference on Power Electronics, Machines and Drives*. 2-4 April. York, UK: IET. pp. 106-110.
28. Ahmad, M. Z., Sulaiman, E. & Kosaka, T. Optimization of outer-rotor hybrid excitation FSM for in-wheel direct drive electric vehicle. *IEEE International Conference on Mechatronics*.2015. pp. 691-696
29. Sulaiman, E. & Kosaka, T. Parameter sensitivity study for optimization of field-excitation flux switching synchronous machine for hybrid electric vehicles. in *7th IEEE Conference on Industrial Electronics and Applications (ICIEA)*. 2012. pp. 52-57.

30. Rauch, S.E. & Johnson, L. J. Design principles of flux-switch alternators. *Transactions of AIEE, Power Apparatus and Systems*, 1955.

31. J. H. Walker, "The theory of the inductor alternator*," J. Inst. Electr. Eng. - Part II Power Eng.*, vol. 89, no. 9, pp. 227–241, 1942.

32. Lawrenson, P. J. Developments in the performance and theory of segmental-rotor reluctance motors. *Proc. IEE*. 1967. 114 (5).

33. Ahmad, M. Z., Sulaiman E., Haron, Z. A., Khan, F. & Mazian, M. A. Initial design configuration of outer rotor hybrid excitation flux switching machine for direct drive applications. *IEEE International Conf. on Power and Energy*. 2012.

34. Pollock C. & Wallace, M. The flux switching motor, a dc motor without magnets or brushes. in *Proceeding of IEEE 34th Industry Applications Society Annual Meeting (IAS)*.1999. 3, pp. 1980–1987.

35. Dasgupta, A. K., Analytical Method to find the Best Number of Stator and Rotor Teeth of Inductor Alternator for 3-phase sinusoidal voltage generation. *AIEE Trans. Power App. Syst*., 1960. 79 (50). pp. 674–679.

36. Schao, Y., Nick, J., Baker, Mecrow, B. C., Hilton, C., Sooriyakumar, G., Perovic, D. K. & Fraser, A. Cost reduction of a permanent magnet in-wheel electric vehicle traction application. *IEEE International Conference on Electric Machines*. 2014. pp. 443-449.

37. Bangura, J. F. Design of high-power density and relatively high efficiency flux-switching motor. *IEEE Trans. Energy Conversion*. 2006. 21(2), pp. 416-424.

38. Chen. J. T., Zhu, Z. Q. Iwasaki S. and. Deodhar R. Low cost flux switching brushless AC machines. in *Proceeding of IEEE Vehicle Power and Propulsion Conf. (VPPC)*. 2010.

39. Zho, Y. J. & Zhu, Z. Q, Comparison of low-cost single-phase wound-field switched-flux machines. *IEEE Trans. Ind. Appl*. 2014. 50(5). pp. 3335-3345.

40. Tang, Y., Paulides, J. J. H., Motoasca, T. E. & Lomonova, E. A. Flux-switching machine with DC excitation. *IEE Trans Magn*., 2012. 48(11), pp. 3583-3586.

41. Pollock, H., Pollock, C., Walter, R. T. & Gorti, B. V. Low cost, high power density, flux switching machines and drives for power tools. in Proceeding of *IEEE Record of the Industrial Applications Conference, IAS Annual Meeting*. 2003. pp. 1451–1457.

42. Lian, G., Gu, G., Cheng, Y., Tao, J., Wang, S & Chen, X. Comparative study on switched reluctance and flux-switching machines with segmental rotors. *In 18th IEEE International Conference on Electrical Machines and Systems (ICEMS).* 2015. pp. 845-848

43. Torkaman, H., Afjei, E. & Toulabi. M. S. New double-layer-per-phase isolated switched reluctance motor: concept, numerical analysis, and experimental confirmation. *IEEE Transactions on Industrial Electronics*. 2012. 59 (2). pp. 830-838.

44. Hoang, E., Hlioui, S., Lecrivain, M. & Gabsi, M. Experimental comparison of lamination material case switching flux synchronous machine with hybrid excitation. in *Proc. of European Conf. Power Electron Application* 2009. pp. 1-7.

45. Hlioui, S., Amara, Y., Hoang, E., Lecrivain M. & Gabsi, M. Overview of hybrid excitation synchronous machine technology. in *International Conf. Electr. Eng. Software Application (ICEESA).* 2013. pp. 1-10.

46. Gaussens, B., Hoang, E., Lecrivain, M., Manfe, P. & Gabsi, M. Hybrid-excited flux-switching machine for high speed DC-alternator applications. *IEEE Trans. Ind. Electron*. 2014. 61(6), pp. 2976-2989.

47. Liao, Y., Liang, F. & Lipo, T. A. A novel permanent magnet motor with doubly salient structure. in Proc. Conf. Rec. *IEEE IAS Annual Meeting*. 1992. pp. 308-314.

48. Hua, W., Cheng, M. & Zhang, G. A novel hybrid excitation flux-switching motor for hybrid vehicles. *IEEE Trans. Magnetics*. 2009. 45(10). pp. 4728-4731.

49. Zhu, Z.Q. Switched flux permanent magnet machines: Innovation continues. in *Proc. Int. Conference on Electrical Mach. Systems (ICEMS)*. 2011. pp. 1-10.

50. Erwan S. *Design studies on less rare-earth and high-power density flux switching motors with hybrid excitation/wound field excitation for HEV drives.* PhD thesis, Nagoya Institute of Technology Nagoya Japan; 2012.

51. Hua, W., Su, P., Tong, M. & Meng, J. Investigation of a five-phase E-Core hybrid-excitation flux-switching machine for EV and HEV Applications. *IEEE Transactions on Industry Applications*. 2016. 53 (1). pp. 124-133.

52. Chen, J.T., Zhu, Z. Q., Iwasaki, S. & Deodhar, R. A novel E-core flux switching PM brushless AC machine. in *Proceeding of IEEE Energy Conversion Congress and Exposition*. 2010. pp. 3811–3818.

53. Hoang, E., Lecrivain, M. & Gabsi, M. A new structure of a switching flux synchronous polyphased machine with hybrid excitation. in *Proc. Eur. Conf. Power Electron. Applications.* 2007. pp.1–8.

54. Deodhar, R. P., Andersson, S., Boldea, I. & Miller, T. J. The flux-reversal machine: A new brushless doubly-salient permanent-magnet machine. *IEEE Transactions on Industry Applications*, 1997. 33(4), 925-934.

55. Jusoh, L. I., Erwan, S., Kumar, R., Bahrim, F. S. & Omar, M. F. Preliminary studies of various rotor pole number for permanent magnet flux switching machines. *International Journal of Applied Engineering Research*. 2017. 12 (7). pp. 1377-1382

56. Syed, Q. A. S., Kurtović, H. & Hahn, I. New single-phase flux switching axial flux permanent magnet motor. *IEEE Transactions on Magnetics*. 2017. 53(11). pp. 1-5.

57. L. Hao, L., Lin, M., Zhao, X. & Luo, H. Analysis and optimization of EMF waveform of a novel axial field flux-switching permanent magnet machine," *in Proceeding of International Conference on Electrical Machine System*, pp. 1-6.

58. Hoang, E., Ahmed, H. B. & Lucidarme, J. Switching flux permanent magnet polyphased synchronous machines. In *EPE* 97.

59. Fei, W. Z. & Shen, J. X. Comparative study and optimal design of PM switching flux motors. In *Proceedings of the 41st International Universities Power Engineering Conference*. 2006. 2. pp. 695-699.

60. Xu, W., Zhu, J., Zhang, Y., Guo, Y. & Lei, G. New axial laminated-structure flux-switching permanent magnet machine with 6/7 poles. IEEE Transactions on magnetics. 2011. 47(10). pp. 2823-2826.

61. Sanabria-Walter, C., Polinder, H., & Ferreira, J. A. High-torque-density high-efficiency flux-switching PM machine for aerospace applications. *IEEE journal of emerging and selected topics in power electronics*.2013. 1(4). pp. 327-336.

62. Thomas, A., Zhu, Z. Q., Jewell, G. W. & Howe, D. Flux-switching PM brushless machines with alternative stator and rotor pole combinations. in

IEEE International Conference on Electrical Machines and Systems. 2008. pp. 2986-2991.

63. Xu, W., Lei, G., Wang, T., Yu, X., Zhu, J. & Guo, Y. Theoretical research on new laminated structure flux switching permanent magnet machine for novel topologic plug-in hybrid electrical vehicle. *IEEE Transactions on magnetics*. 2012. 48(11). pp. 4050-4053.

64. Somesan, L., Padurariu, E., Viorel. I. A. & Szabo, L. Design of a permanent magnet flux-switching machine," in *Proceeding of ELEKTRO*. 2012. pp. 256-259.

65. Zhu, Z. Q., & Chen, J. T. Advanced flux-switching permanent magnet brushless machines. *IEEE Transactions on Magnetics*. 2010. 46 (6). pp. 1447-1453.

66. Zhu, Z. Q. & Evans, D. Overview of recent advances in innovative electrical machines - with particular reference to magnetically geared switched flux machines. in *17th International Conference on Electrical Machines and Systems, ICEMS*. 2015.

67. Cai, J., Lu., Q. Jin., Y., Chen, C. & Ye, Y. Performance investigation of multi-tooth flux- switching PM linear motor. in *International Conference on Electrical Machines and Systems (ICEMS)*. 2011, pp. 1 – 6, 2011.

68. Li, F., Hua, W., Tong, M., Zhao, G. & Cheng, M. Nine-phase flux-switching permanent magnet brushless. *IEEE Trans. Magn*. 2015. 51(3). pp. 34–37.

69. Xue, X., Zhao, W., Zhu, J., Liu, G., Zhu, X. & Cheng, M. Design of five-phase modular flux-switching permanent-magnet machines for high reliability applications. *IEEE Transactions on magnetics*. 2013. 49(7). pp. 3941-3944.

70. Raminosoa, T., & Gerada, C. Fault tolerant winding technology comparison for flux switching machine. in *the XIX International Conference on Electrical Machines-ICEM*. 2010. pp. 1-6). IEEE.

71. Chen, J. T., Zhu, Z. Q., Iwasaki, S. & Deodhar, R. A novel E-core flux switching PM brushless AC machine. in *Proceeding of IEEE Energy Conversion Congress and Exposition*. 2010. pp. 3811–3818.

72. Fei, W. Z. & Shen, J. X. Novel permanent magnet switching flux motors. in Proceedings of the *41st IEEE International Universities Power Engineering Conference*. 2006. 2, pp. 729-733.

73. G. Henneberger, I.A. Viorel, Variable Reluctance Electrical Machines. Aachen (Germany): Shaker Verlag, 2001.

74. L. Someşan, E. Pădurariu, I.A. Viorel, L. Szabó, "Design of a permanent magnet flux-switching machine," in Proceedings of the 9th International Conference ELEKTRO '2012,Žilina - Rajecké Teplice (Slovakia), 2012, pp. 256-259.

75. A.S. Thomas, Z.-Q. Zhu, R.L. Owen, G.W. Jewell, D. Howe, “Multiphase flux-switching permanent-magnet brushless machine for aerospace application," *IEEE Transactions on Industry Applications*, vol.45, no. 6, pp. 1971-1981, 2009.

76. A. Thomas, Z. Zhu, L. Wu, "Novel modular-rotor switched-flux permanent magnet machines," *IEEE Transactions on Industry Applications*, vol. 48, no. 6, pp. 2249-2258, 2012

77. P. J. Lawrenson and S. K. Gupata, “Developments in the performanceand theory of segmental-rotor reluctance motors,” *Proc. Inst. Elect. Eng.*,vol. 114, no. 5, pp. 645–653, May 1967.

78. P. J. Lawrenson, S. K. Gupata, and S. R. Murthy Vamaraju, “Multispeed performance of segmental-rotor reluctance machines,” *Proc. IEE*,vol. 115, no. 5, pp. 695–702, May 1968.

79. P. J. Lawrenson and S. K. Gupata, “Fringe and permeance factors forsegmented-rotor reluctance machines,” *Proc. Inst. Elect. Eng.,* vol. 118,no. 5, pp. 669–674, May 1971.

80. B. C. Mecrow, J. W. Finch, E. A. El-Kharashi, and A. G. Jack, “Switchedreluctance motors with segmental rotors,” *Proc. Ind. Elect. Eng.—Elect.Power Appl.*, vol. 149, no. 4, pp. 245–254, Jul. 2002.

81. B. C. Mecrow, E. A. El-Kharashi, J. W. Finch, and A. G. Jack, “Segmentalrotor switched reluctance motors with single-tooth windings,” *Proc. Inst.Elect. Eng.—Elect. Power Appl.,* vol. 150, no. 5, pp. 591–599, Sep. 2003.

82. R. Hall, A. G Jack, B. C. Mecrow, and A. J. Mitcham, “Design and initialtesting of an outer rotating segmented rotor switched reluctance machinefor an aero-engine shaft-line-embedded starter/generator,” in *Proc. IEEE Int. Conf. Elect. Mach. Drives*, May 2005, pp. 1870–1877.

83. D. J. Powell, G. W. Jewell, D. Howe, and K. Atallah, "Rotor topologies for a switched-reluctance machine for the 'more-electric' aircraft engine, "*Proc. Inst. Elect. Eng.—Elect. Power Appl.,* vol. 150, no. 3, pp. 311–318,May 2003.

84. D. J. Powell, G. W. Jewell, S. D. Calverley, and D. Howe, "Iron loss in a modular rotor switched reluctance machine for the 'more-electric' aeroengine," *IEEE Trans. Mag*n., vol. 41, no. 10, pp. 3934–3937, Oct. 2005.

85. A. G. Jack, B. C. Mecrow, and J. A. Haylock, "A comparative study of permanent magnet and switched reluctance motors for high-performance fault-tolerant applications," *IEEE Trans. Ind.* Appl., vol. 32, no. 4,pp. 889–895, Jul./Aug. 1996

86. Kumar R.H. *Refinement of outer rotor permanent magnet flux switching machine for downhole application*. Master's thesis. Universiti Tun Hussein Onn Malaysia; 2017.

87. Shirani, M., Abbass A., Saeed. & Jalil Jamali. A review on recent applications of brushless DC electric machines and their potential in energy saving. *Energy Equipment and Systems*. 2015. 3 (1). pp. 57-71.

88. Zhou, Y. J. & Zhu, Z. Q. Comparison of wound-field switched-flux machines. *IEEE Transactions on Industry Applications*. 2015. 50 (5). pp. 3314-3324

89. Omar, M. F., Sulaiman, E., Khan, F., Romala, G. M, & Husin, Z. A. Comparison between single phase and three phase FEFSM with non-overlap windings and salient rotor. *ARPN Journal of Engineering and Applied Sciences*. 2013. pp. 1-5.

90. Ilhan, E., Kremers., M. F. J. Motoasca, E. T., Paulides, J. J. H. & Lomonova, E. A. Sensitivity analysis for phase inductances in flux-switching PM machines. in *Proc. Int. Conference on Electrical Machines*. 2012. pp.763-768.

91. Yang, Y., Yang., X, Chen, P. & Wang, X. Electromagnetic performance analysis of hybrid excited segmental rotor flux switching machine. *IEEE Transactions on Magnetics*. 2018. pp.1–5.

92. Okamoto, S., Denis, N., Kato, Y., Ieki, M. & Fujisaki, K. Core loss reduction of an interior permanent-magnet synchronous motor using amorphous stator core. *IEEE Transactions on Industry Applications*. 2016. 52(3), pp. 2261-2268.

93. Wang, Z., Enomoto, Y., Masaki, R., Souma, K., Itabashi, H. & Tanigawa, S. Development of a high-speed motor using amorphous metal cores. In *8th International Conference on Power Electronics-ECCE*. 2011. pp. 1940-1945.

94. Ribberink, Hajo, and Evgueniy Entchev. Electric vehicles - A one-size-fits-all solution for emission reduction from transportation. IEEE World Electric Vehicle Symposium and Exhibition (EVS27). 2013. pp. 1-7.

95. Xiaohe, M., Yang, Y., Rong, S., Jet, T. K., Vaiyapuri, V., Amit, G. & Chandana, G. Comparative analysis of flux switching machines between toothed rotor with permanent magnet excitation and segmented rotor with field coil excitation. in *IECON Annual Conference of the IEEE Industrial Electronics Society*. 2016. pp. 1610-1615.

96. Sun, W., Li, Y., Xu, G. & Zhang, N. Vibration control of in-wheel SRM for electric vehicle applications. in INTERNOISE 43rd *International Congress on Noise Control Engineering: Improving the World Through Noise Control*. 2014.

97. Pang, Y., Zhu, Z. Q., Howe, D., Iwasaki, S., Deodhar, R. & Pride, A. Eddy current loss in the frame of a flux-switching permanent magnet machine. *IEEE Trans. Magnetics*. 42 (10). pp. 3413-3415.

98. Zhu, Z. Q., Pang, Y., Chen, J. T., Owen, R. L, Howe, D., Iwasaki, S., Deodhar, R. & Pride, A. Analysis and reduction of magnet eddy current loss in flux-switching permanent magnet machines. in *Proc. 4th IET Conference on Power Electron., Machines Drives*. 2008. pp. 120-124.

99. Ilhan, E., Kremers., M. F. J. Motoasca, E. T., Paulides, J. J. H. & Lomonova, E. A. Sensitivity analysis for phase inductances in flux-switching PM machines. in *Proc. Int. Conference on Electrical Machines*. 2012. pp.763-768.

100. Chen, J. T., Zhu, Z. Q., Iwasaki, S. & Deodhar, R. Comparison of losses and efficiency in alternate flux-switching permanent magnet machines. in *Proc. International Conference on Electrical Machines*. 2010. pp.1-6.

101. Dyck, D. N. & Lowther, D. A. Automated design of magnetic devices by optimizing material distribution. *IEEE Trans. Magn*. 32 (3). pp. 1188–1192.

102. Byun, J. & Hahn, S. Topology optimization of electrical devices using mutual energy and sensitivity. *IEEE Transactions on Magnetics*, 35 (5). pp. 3718–3720.

103. Im, C., Jung, H. & Kim, Y. Hybrid genetic algorithm for electromagnetic topology optimization. *IEEE Trans. Magn*., 2003. 39 (5). pp. 2163–2169.

104. Wang, S., Youn, D., Moon, H. & Kang, J. Topology optimization of electromagnetic systems considering magnetization direction. *IEEE*

Transactions on Magnetics. 2005. 41 (5). pp. 1808–1811.

105. Wang, S., Youn, D., Moon., H. & Kang, J. Topology optimization of electromagnetic systems considering magnetization direction. *IEEE Trans. Magn*., 2005. 41(5). pp. 1808–1811.

106. Iles-Klumpner, D., Risticevic, M. & Boldea, I. Advanced optimization design techniques for automotive interior permanent magnet synchronous machines. in *IEEE International Conference on Electric Machines and Drives,* 2005. (pp. 227-234.

107. Kim, D. H., Sykulski, J. K., & Lowther, D. A. The implications of the use of composite materials in electromagnetic device topology and shape optimization. *IEEE Transactions on Magnetics,* 45(3), 1154-1157.

108. Choi, J. S., & Yoo, J. (2009). Structural topology optimization of magnetic actuators using Genetic algorithms and ON/OFF sensitivity. *IEEE Transactions on Magnetics*, 45(5), 2276-2279.

109. Sulaiman, E., Kosaka, T. & Matsui, N. Parameter optimization study and performance analysis of 6S-8P permanent magnet flux switching machine with field excitation for high speed hybrid electric vehicles. in Proceedings of the *14th IEEE European Conference on Power Electronics and Applications* (pp. 1-9). 2011.

110. Sulaiman, E., Teridi, M. F. M., Husin, Z. A., Ahmad, M. Z., & Kosaka, T. Investigation on flux characteristics of field excitation flux switching machine with single FEC polarity, *The 4th International Conference on Electrical Engineering and Informatics*, (pp. 572 – 579). 2013.

111. Laws AE. An electromechanical transducer with permanent magnet polarization, Technical Note No.G.W.202, Royal Aircraft Establishment, Farnborough, UK, 1952.

112. L. I. Jusoh, E. Sulaiman, M. F. Omar, and H. A. Soomro, “A Comparative Studyof Single - tooth and Multi - tooth Stator of 4S - 8P Permanent Magnet FSM forElectric Bicycle Application,” Int. J. Eng. Technol., vol. 7, no. 4.3, pp. 295–298, 2018.

113. R. Kumar, E. Sulaiman, H. A. Soomro, L. I. Jusoh, F. S. Bahrim, and M. F.Omar, “Design Enhancement and Performance Examination of External Rotor Switched Flux Permanent Magnet Machine for Downhole Application,” IOPConf. Ser. Mater. Sci. Eng., vol. 226, no. 1, p. 012125, 2017.

114. E. Sulaiman, T. Kosaka, and N. Matsui, "Design optimization of 12Slot-10Polehybrid excitation flux switching synchronous machine with 0.4kg permanentmagnet for hybrid electric vehicles," in 8th International Conference on PowerElectronics - ECCE Asia, 2011, pp. 1913–1920

115. Jenal, M., Sulaiman, E., & Kumar, R. A new switched flux machine employing alternate circumferential and radial flux (AlCiRaF) permanent magnet for light weight EV. *Journal of Magnetic*, 21(4), 537-543, 2016.

116. E. Sulaiman, M. Z. Ahmad, T. Kosaka, N. Matsu (2012). Design Optimization Studies on High Torque and High-Power Density Hybrid Excitation Flux Switching Motor for HEV. Procedia Engineering 53(2013) 312-322.

117. Sulaiman, E. B., Khan, F., & Kosaka, T. (2016). Field-excited flux switching motor design, optimization and analysis for future hybrid electric vehicle using finite element analysis. Progress in Electromagnetics Research, 71, 153-166.

118. Jenal, M., Sulaiman, E., Ahmad, M. Z., Khan, F., & Omar, M. F. (2016, September). A new alternate circumferential and radial flux (AlCiRaF) permanent magnet flux switching machine for light weight EV. In 2016 XXII International Conference on Electrical Machines (ICEM) (pp. 2399-2405). IEEE.

119. M. Lin, L. Hao, X. Li, X. Zhao, and Z. Q. Zhu, "A novel axial field fluxswitching permanent magnet wind power generator," *IEEE Trans. Magn.*, vol.47, no. 10, pp. 4457–4460, 2011.

120. [98] C. Yu and S. Niu, "Development of a Magnetless Flux Switching Machine for Rooftop Wind Power Generation," *IEEE Trans. Energy Convers.*, vol. 30, no. 4, pp. 1703–1711, 2015.

121. [99] Z.-C. You, S.-M. Yang, C.-W. Yu, Y.-H. Lee, and S.-C. Yang, "Design of a High Starting Torque Single-Phase DC-Excited Flux Switching Machine," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9905–9913, 2017.

122. [100] M. F. Omar, E. Sulaiman, F. Khan, M. Jenal, and G. M. Romalan, "A new single-phase FEFSM with segmental rotor for conventional fan," in *2016 XXII International Conference on Electrical Machines (ICEM)*, 2016, pp. 2406–2411

123. [178] E. Sulaiman and T. Kosaka, "Parameter sensitivity study for optimization of field-excitation flux switching synchronous machine for hybrid electric vehicles," in *2012 7th IEEE Conference on Industrial Electronics and*

Applications (ICIEA), 2012, pp. 52–57.

124. [179] E. Sulaiman, M. F. Omar, and S. S. Hakami, "Optimization of 6Slots-7Poles &12Slots-14Poles flux-switching permanent magnet machines for plug-in HEV,"in *International Conference on Control, Electronics, Renewable Energy andCommunications (ICCEREC)*, 2016, pp. 220–225.

125. [180] L. I. Jusoh, E. Sulaiman, M. F. Omar, and H. A. Soomro, "A omparative Study of Single - tooth and Multi - tooth Stator of 4S - 8P Permanent Magnet FSM for Electric Bicycle Application," *Int. J. Eng. Technol.*, vol. 7, no. 4.3, pp. 295– 298, 2018.

126. [181] R. Kumar, E. Sulaiman, H. A. Soomro, L. I. Jusoh, F. S. Bahrim, and M. F. Omar, "Design Enhancement and Performance Examination of External Rotor Switched Flux Permanent Magnet Machine for Downhole Application," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 226, no. 1, p. 012125, 2017.

127. [182] E. Sulaiman, T. Kosaka, and N. Matsui, "Design optimization of 12Slot-10Pole hybrid excitation flux switching synchronous machine with 0.4kg permanent magnet for hybrid electric vehicles," in *8th International Conference on Power Electronics - ECCE Asia*, 2011, pp. 1913–1920.

128. [183] E. Sulaiman, T. Kosaka, and N. Matsui, "A novel hybrid excitation flux switching synchronous machine for a high-speed hybrid electric vehicle applications," in *2011 International Conference on Electrical Machines and Systems*, 2011, pp. 1–6.

129. [161] X. Zhu, Z. Shu, L. Quan, Z. Xiang, and X. Pan, "Multi-Objective Optimization of an Outer-Rotor V-Shaped Permanent Magnet Flux Switching Motor Based on Multi-Level Design Method," IEEE Trans. Magn., vol. 52, no. 10, pp. 1–8, 2016.

130. [184] M. Z. Ahmad, E. Sulaiman, and T. Kosaka, "Optimization of outer-rotor hybrid excitation FSM for in-wheel direct drive electric vehicle," in *IEEE International Conference on Mechatronics (ICM)*, 2015, pp. 691–696.

131. [185] M. Z. Ahmad, E. Sulaiman, and T. Kosaka, "Analysis of high torque and power densities outer-rotor PMFSM with DC excitation coil for in-wheel direct drive," *J. Magn.*, vol. 20, no. 3, pp. 265–272, 2015

132. [187] M. M. A. Mazlan, E. Sulaiman, M. Z. Ahmad, and S. M. N. S. Othman, "Design optimization of single-phase outer-rotor hybrid excitation flux switching motor for electric vehicles," in *IEEE Student Conference on*

Research and Development (SCOReD), 2014, pp. 1–6.

133. [101] M. F. Omar, E. Sulaiman, M. Jenal, R. Kumar, and R. N. Firdaus, "Magnetic Flux Analysis of a New Field-Excitation Flux Switching Motor Using Segmental Rotor," *IEEE Trans. Magn.*, vol. 53, no. 11, pp. 1–4, Nov. 2017.

134. [102] X. Liu and G. R. Slemon, "An improved method of optimization for electrical machines," *IEEE Trans. Energy Convers.*, vol. 6, no. 3, pp. 492–496, 1991.

135. [103] A. Cavagnino, G. Bramerdorfer, and J. A. Tapia, "Optimization of electric Machine Designs-Part I," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9716– 9720, 2017.

136. [104] G. Lei, J. Zhu, Y. Guo, C. Liu, and B. Ma, "A review of design optimization methods for electrical machines," *Energies*, vol. 10, no. 12, pp. 1–31, 2017.

137. [105] A. Cavagnino, G. Bramerdorfer, and J. A. Tapia, "Optimization of Electric Machine Designs - Part II," *IEEE Trans. Ind. Electron.*, vol. 65, no. 2, pp. 1700– 1703, 2018.

138. [106] F. Dubas, A. Sari, D. Hissel, and C. Espanet, "A comparison between CG and PSO algorithms for the design of a PM motor for fuel cell ancillaries," in *2008 IEEE Vehicle Power and Propulsion Conference*, 2008, pp. 1–7.

139. [107] Ke-yan Liu, Wanxing Sheng, and Sheng Cheng, "A novel improved sequential quadratic programming algorithm to solve DG dispatch in distribution system," in *International Conference on Electrical Machines and Systems (ICEMS)*, 2013, pp. 1415–1420.

140. [108] A. Kakaee and M. Keshavarz, "Comparison the Sensitivity Analysis and Conjugate Gradient algorithms for Optimization of Opening and Closing Angles of Valves to Reduce Fuel Consumption in XU7 / L3 Engine," *Int. J. Automot. Eng.*, vol. 2, no. 3, pp. 143–155, 2012.

141. [109] H. Razik, C. Defranoux, and A. Rezzoug, "Identification of induction motor using a genetic algorithm and a quasi-Newton algorithm," in *7th IEEE International Power Electronics Congress. Technical Proceedings (CIEP)*, 2000, pp. 65–70.

APPENDIX A

LIST OF PUBLICATIONS AND AWARDS

Journals (Scopus Indexed)

(i) **Irfan Ali Soomro**, Erwan Sulaiman, Hassan Ali Soomro & Syed Muhammad Naufal Bin Syed Othman, Performance Analysis of Permanent Magnet Flux Switching Machine Based on Modular Rotor, *International Journal of Advanced Trends in Computer Science and Engineering,* 2020. (Scopus Indexed). Accepted.

(ii) **Irfan Ali Soomro**, Erwan Sulaiman, Hassan Ali Soomro & Laili Iwani Jusoh, Advancement of Modular Rotor Permanent Magnet Flux Switching Motor Using Local Optimization Approach, *International Journal of Advanced Trends in Computer Science and Engineering,* 2020. (Scopus Indexed). Accepted

Proceedings (Scopus Indexed)

(i) **Irfan Ali Soomro**, Erwan Sulaiman, Hassan Ali Soomro. Modular rotor Based Permanent Magnet Flux Switching Machine for Light Weight EV. *IEEE 15th International Colloquium on Signal Processing & Its Applications (CSPA) 2019*: IEEE. pp. 182-185.

(ii) **Irfan Ali Soomro**, Erwan Sulaiman, Hassan Ali Soomro & Faisal Amin Comparative Study on a Modular Rotor and AlCiRaF Permanent Magnet Flux Switching Machine. *IEEE International Conference on Automatic Control and Intelligent Systems (I2CACIS) 2019*: IEEE pp. 199-203.

(iii) **Irfan Ali Soomro**, Erwan Sulaiman, Hassan Ali Soomro & Faisal Amin, Performance analysis of modular rotor based permanent magnet flux switching machine for lightweight electric vehicles. *International Scientific Forum (ISF) 2019.*

(iv) **Irfan Ali Soomro**, Erwan Sulaiman, Mahyuzie Jenal, Hassan Ali, Overview of inner rotor radial permanent magnet machines for electric vehicles. *The 1st International Conference on Advanced Sciences and Engineering 2020 (ICASE 2020)* (Accepted)

Award

(i) **Gold Medal** in International Research and Innovation Symposium and Exposition (2019), Irfan Ali Soomro, Dr. Erwan Sulaiman and Hassan Ali Soomro, "SalMoN Motor (*Salient stator, Modular rotor, Non-overlapping winding*)" UTHM. 24th September 2019.